# Earthquake Loss Estimates for the San Francisco Bay Area: the ten most likely major events in the next thirty years

Mary Lou Zoback[1], Johanna Fenton and Kevin Miller[2], Chris Wills and Badie Rowshandel[3], and Jeanne Perkins[4]

## Abstract

The U. S. Geological Survey-led Working Group on California Earthquake Probabilities has determined that there is a 62% chance of one or more magnitude 6.7 earthquakes in the greater San Francisco Bay area over the next 30 years. We present a summary of loss estimates for the ten most likely damaging earthquakes forecast to strike the Bay Area over the next 30 years as determined by the Working Group. These earthquakes occur on six of the seven major fault systems in the Bay Area and range in size from a magnitude 6.7 event on a blind thrust underlying Mt. Diablo to a magnitude 7.9 repeat of the 1906 rupture on the San Andreas fault in northern California.

Our loss estimates are determined using the Federal Emergency Management Agency's nationally recognized earthquake loss estimation model, HAZUS, and incorporate computed ground-shaking inputs for the scenario events. We find that seven of the ten forecast earthquakes would cause social and economic disruption at least equivalent to the 1989 magnitude 6.9 Loma Prieta earthquake, which resulted in approximately $6 billion in direct physical damage and $10 billion in total economic losses. We compare these results to annualized loss estimates based on the long-term regional seismic hazard.

Our estimates probably underestimate the impact of the scenario earthquakes. We calculated building damage, displaced households, casualties and related economic loss using HAZUS99 service release 2 which utilizes population and building inventory from the 1990 census. Present Bay Area population is 7.05 million, more than a 13% increase over the 1990 census value. Also, HAZUS, as implemented, does not determine damage to many major facilities or lifelines, such as drinking water systems (including the Hetch-Hetchy aqueduct), Bay Area ports, and light rail systems. It also does not calculate the ripple effects of damage to lifelines on the economy of the Bay Area and California.

An Association of Bay Area Governments (ABAG) analysis of post-earthquake housing needs using a refined Bay Area residential inventory forecasts more than 150,000 uninhabitable housing units for both a repeat of the 1906 quake or a magnitude 6.9 rupture of the entire Hayward fault. In contrast, the HAZUS estimates of displaced households for those same events are a factor of 2.5 to 6 lower due to inaccurate inventories and other factors. Nevertheless, our estimates of casualties and damage to structures, combined with the probabilities of these events, provide residents and decision makers in the San Francisco Bay Area with vital information to assess their exposure and prepare for future damaging earthquakes.

## Introduction

[1] Earthquake Hazards, U. S. Geological Survey, 345 Middlefield Rd., MS 977, Menlo Park, CA 94025
[2] California Governor's Office of Emergency Services, 1300 Clay St., Oakland, CA 94612
[3] California Geological Survey, 801 K Street, MS 14-33, Sacramento, CA 95814
[4] Association of Bay Area Governments, P. O. Box 2050, Oakland, CA 94604

The San Francisco Bay Area experienced large and destructive earthquakes in 1838, 1868, 1906, and 1989 and future large earthquakes are a certainty. The U.S. Geological Survey-led Working Group on California Earthquake Probabilities has concluded that there is a 62% probability of at least one major, damaging earthquake striking the greater San Francisco Bay region over the next 30 years (2002-2031) (Working Group on Earthquake Probabilities, 2003). Such earthquakes are considered most likely to occur on one of seven fault systems subparallel to the San Andreas fault (Figure 1), and for which historic and geologic evidence suggests similar-sized events have occurred in the past. The Working Group considered "major", damaging earthquakes as those with moment magnitude **M** $\geq$ 6.7. Experience from recent earthquakes in Northridge, California (**M**6.7, 1994, 60 killed, $20B in direct losses, $42B total losses) and Kobe, Japan (**M**6.9, 1995, 6000 killed, $147B in direct losses) has demonstrated, earthquakes of this size can have a profound impact on the social and economic fabric of densely urbanized areas.

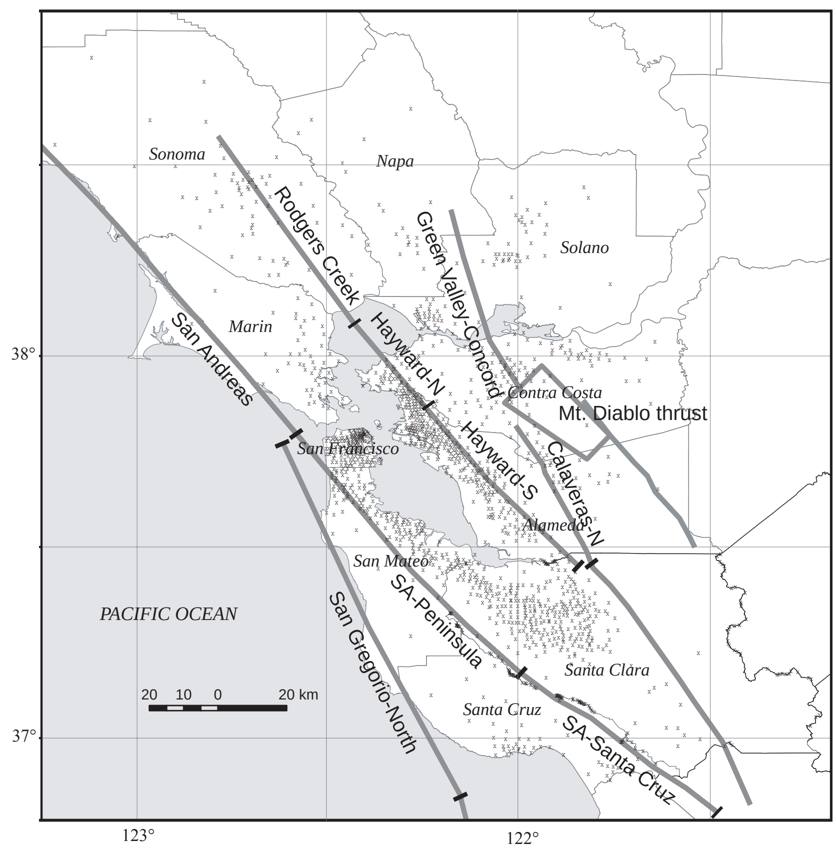


Figure 1. Ten-county San Francisco Bay area study region. Fault segments for scenario events are shown by heavy grey lines. Census tract centroids shown by *x*.

The threat and consequences of damaging earthquakes in the San Francisco Bay Area have been described in previous earthquake-planning scenarios published by the California Geological Survey (CGS) (Toppozada, et al., 1994, Steinbrugge, et al., 1987, Davis et al., 1982). In addition, the Association of Bay Area Governments (ABAG) has generated suites of earthquake-loss scenarios using geographic information system (GIS) software for the San Francisco Bay Area (Perkins, 1998, 1999; Perkins and Boatwright, 1995). These earthquake-scenario studies have led to an understanding of regional transportation and housing issues following significant earthquakes.

The purpose of this study is to provide a sense of the impact of specific future, high-likelihood earthquakes on the Bay Area through a quantitative earthquake loss estimation using HAZUS, a risk assessment modeling system developed by the Federal Emergency Management Agency (FEMA) in cooperation with the National Institute of Building Science (NIBS). FEMA developed HAZUS to provide a standardized national risk assessment system for mitigation and planning purposes. The software is available for free to local governments and other parties interested in investigating their potential vulnerability to earthquakes at the FEMA website: http://www.fema.gov.

We select for study the ten most likely major earthquakes within the Bay Area as identified by the USGS-led Working Group (Working Group on California Earthquake Probabilities, 2003). The selected quakes, their mean magnitudes and probability of occurring in the next 30 years are summarized in Table 1 and their locations are given in Figure 1. The **M**7.9 rupture of the entire northern California San Andreas fault, a repeat of the 1906 San Francisco earthquake, represents a "worst case" scenario for the region. The probability for this event is 4.7%. Probabilities of the ten most likely earthquakes vary from a high of about 15% for a **M**7.0 event on the Rodgers Creek fault to a low of 3.5% for a **M**7.4 rupture of the Peninsula and Santa Cruz segments of the San Andreas fault.

Table 1. The ten most likely significant earthquakes forecast for the San Francisco Bay Area arranged in descending order of probability of occurrence in 2002-2031. (Working Group Report on California Earthquake Probabilities, 2003).

| **Fault rupture** | **30-year probability** | **Magnitude** |
|---|---|---|
| Rodgers Creek | 15.2% | 7.0 |
| Calaveras - North | 12.4% | 6.8 |
| Hayward - South | 11.3% | 6.7 |
| Hayward – North + South | 8.5% | 6.9 |
| Mt. Diablo | 7.5% | 6.7 |
| Green Valley-Concord | 6.0% | 6.7 |
| San Andreas-Entire N. CA segment (repeat 1906) | 4.7% | 7.9 |
| San Andreas-Peninsula segment | 4.4% | 7.2 |
| San Gregorio - North | 3.9% | 7.2 |
| San Andreas - Peninsula + Santa Cruz segment | 3.5% | 7.4 |

For the ten selected earthquakes, our results offer decision makers a relative comparison of estimated comprehensive economic effects on the population and the built environment. These results are discussed in the context of actual Bay Area losses in the 1989 **M**6.9 Loma Prieta earthquake as well as more detailed impact studies conducted by the ABAG. For perspective, we also compare these deterministic scenario results with annualized earthquake loss estimates computed by the California Geological Survey (CGS) using HAZUS with the probabilistic seismic hazard maps as input. These hazard maps integrate the hazards of all future earthquakes (both on and off the main faults) with their likelihood of occurring.

We believe these predictions on the impact of future earthquakes in the San Francisco Bay region can be useful in several ways. Emergency response personnel can use these scenario-based estimates to more realistically plan for response and recovery from potential likely events. Decision makers can use details on the distribution and extent of likely damage to prioritize seismic mitigation projects.

## Loss Estimation Methodology

Our results were generated using HAZUS99 Service Release 2 (software and manuals available at: http://www.fema.gov/hazus). We used a consistent, ten-county, San Francisco Bay Area study region (counties included are named on Figure 1) to compare the effects of the ten most likely scenario earthquakes, all of which occur on faults within the region. Our Bay Area study region covers 7,573 square miles, contains over 2,335,000 households and has a population of 6,253,000 (values taken from the 1990 Census Bureau data which is the default in HAZUS99 Service Release 2). We used the default HAZUS national-scale building and infrastructure inventory (also derived from 1990 Census data) in our analysis since it is the only complete inventory for the entire region. This inventory estimates 1,704,000 total buildings for the Bay Area study region: 74% residential; 19% commercial; 5% industrial, and 2% other (religion, education, government, and agriculture). This building stock has an estimated aggregate total replacement value of $366,177,000 in 1994 dollars. The results presented here will represent minimum values since the 2000 Census data indicate a population of slightly more than 7 million (13% growth) and there was considerable residential and commercial construction throughout the region in the 1990's.

The basic analysis unit in HAZUS is the census tract, defined by the U. S. Census Bureau as a geographic region including residents with similar characteristics; each census tract averages about 4,000 people (U. S. Census Bureau, 2000). Our ten-county study region contains approximately 1,400 census tracts. Within the region the census tract size varies from significantly less than one square mile to 584 square miles, depending on the population density.

It is significant to note that in HAZUS, the exposure and potential damage for the entire census tract is computed at a single point, the centroid of the tract. This means one set of ground motion parameters is applied to all structures and infrastructures within the tract, regardless of how actual ground motions and local soil conditions may vary within the tract. The location of these centroids is given on Figure 1; the distribution of these centroids provides a good proxy for population density within the region.

## Specifying Input Parameters for the Scenario Events

Four ground motion parameters provide the basic input for the HAZUS damage calculations: peak ground acceleration (PGA), peak ground velocity (PGV), and spectral accelerations (SA) at 0.3 and 1.0 second periods. These four ground motion parameters are generally used to estimate different types of damage to the built environment. PGA is indicative of the severity of ground shaking, it can be combined with PGV to obtain a proxy for the Modified Mercalli Intensity (MMI) observation scale of shaking and damage (Wald et al., 1999a). PGV is also correlated to areas of expected damage to underground pipelines such as water, wastewater, oil, and gas. Spectral accelerations at 0.3 and 1.0 seconds are used to calculate expected damage to different structures. Shorter, more stiff buildings, generally three stories or less, are assumed to respond to the spectral accelerations at 0.3 seconds, while taller, more flexible buildings, generally ten stories, are assumed to respond to the spectral accelerations at 1.0 seconds.

We chose the "user supplied" input option for HAZUS to specify our scenario events. Values of the four required ground motion parameters were computed using the same methodology employed by the USGS in producing automated, near real-time, web-based "ShakeMaps" that are produced after all significant Bay Area and Southern California earthquakes (Wald et al., 1999b).

Predictive scenario ShakeMaps have been produced for all 41 of the potential rupture sources defined by the Working Group on California Earthquake Probabilities, see: http://quake.wr.usgs.gov/research/strongmotion/effects/shake/archive/scenario.html. The scenario ShakeMaps are valuable in guiding emergency response planning as well as providing the predicted ground motion parameters suitable for direct input into HAZUS. The GIS-based grids of required ground motion inputs for all the scenario events can be downloaded from this same web site. It is recommended that all groups interested in using HAZUS for loss estimation for specific Bay Area events use these scenario ShakeMap ground motion files for their input. This will assure standard inputs for a given scenario for loss estimation by different groups for different purposes and areas.

Although the scenario Shake Maps represent the current consensus on likely earthquakes and ground motion calculations, differences in these procedures can have a significant impact on the final results. As part of this study, the California Geological Survey (CGS) calculated ground motions for the same earthquake scenarios, changing only the calculation of amplification of seismic shaking in near-surface soils. This seemingly minor technical detail, which involves a choice between two models that are well documented in the scientific literature, makes a difference of up to 30% in the calculation of building losses, and differences of 50-100% in the estimated number of displaced households.. As more strong motion data are recorded and our understanding of earthquake ground shaking continues to improve, and we develop more complete building inventories, these loss calculations could be refined substantially.

## Results

HAZUS produces a suite of estimates of the level of damage to buildings and infrastructure, possible injuries and casualties, and resulting economic losses, both direct and indirect. Although there are a variety of uncertainties associated with the absolute value of HAZUS loss estimates (discussed in the next section), comparison of loss estimates for different events using the same methodology provides planners with a valid relative comparison among the ten scenarios described here. These loss estimates can be compared both to actual damage and losses in the Loma Prieta earthquake. For calibration of our results, we also ran HAZUS using a ShakeMap for the Loma Prieta earthquake based on actual ground motion recordings as input, allowing actual losses for that event to be compared directly with those using the methodology we are employing.

HAZUS runs produce a suite of standard reports for each event. In addition to a an overall summary "global" report, there are detailed reports covering damage to buildings and highways, economic loss for buildings, estimates of casualty, debris, displaced households and shelter needs, and post-event functionality of critical facilities.

## Building-Related Economic Losses

One of the most direct measures of earthquake impact and loss is the damage to buildings and structures. HAZUS uses knowledge of model building types (FEMA, 1992) and estimates of ground shaking to calculate the extent and severity of damage to structural and non-structural components of a building. The resulting damage state is translated into dollar losses for repair and replacement costs of the building stock (building damage cost, given in 1994 dollars. HAZUS uses this damage to estimate the associated losses of building contents and business inventory. In addition, income losses due to business interruption and rental income losses resulting from the restriction of the building's ability to function properly are also computed. All of these losses sum to produce the total building economic losses which is compare in Figure 2 to the building damage cost as defined above.

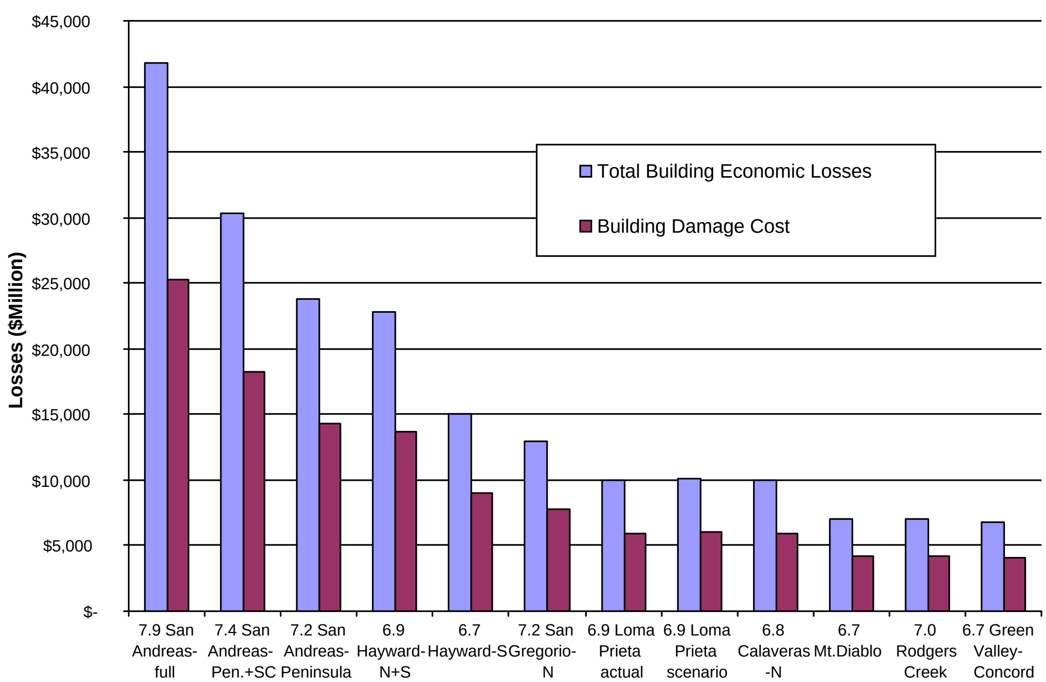


Figure 2. Building-related economic losses for the ten scenario events and Loma Prieta.

Figure 2 compares the building damage cost (dark gray bars) and total building-related economic losses (light gray bars) for the ten scenario events with actual and computed losses for the 1989 **M**6.9 Loma Prieta earthquake. As Figure 2 demonstrates, for seven of the ten scenario events the computed building-related losses (both repair and replacement as well as total losses) are at least as large as Loma Prieta. Note that the actual and computed losses for the 1989 Loma Prieta earthquake agree quite well, this is not surprising since Loma Prieta was used as a calibration event in the development of HAZUS. The three East Bay events with projected losses less than Loma Prieta, the **M**6.7 Mt. Diablo, the **M**7.0 Rodgers Creek, and the **M**6.7 Concord-Green Valley earthquakes, are all centered in regions of low population density (see census tract centroid locations in Figure 1) and are located in primarily new, well-constructed residential areas. However, it should be noted that there has been significant growth and development in the North and East Bay in the vicinities of these faults, since the 1990 census from which the building inventory was derived. Future losses will undoubtedly be much larger for these events.

While estimated losses generally correlate with magnitude, the Hayward fault events stand out as a notable exception. The high losses for the Hayward events are the result of the high exposure directly along the fault trace (note the high density of census tract centroids directly along and adjacent to the fault shown in Figure 1). By comparison, much of the San Andreas trace on the Peninsula runs through relatively unihabited Coast Ranges or the fault runs offshore, thus in the San Andreas case there is relatively less exposure directly adjacent to the fault where ground motions are largest.

## Impact on Housing

The **M**6.9 1989 Loma Prieta earthquake caused a total of over 16,000 housing units to be uninhabitable throughout the ten-county Bay Area. By contrast, the 1994 **M**6.7 Northridge earthquake, centered directly under a major residential region in the greater Los Angeles urban area, resulted in over 46,000 uninhabitable housing units. These events demonstrate the significant impact and disruption to urban populations caused by earthquakes. Based on predicted building damage, HAZUS estimates the number of displaced households due to loss of habitability from damage to the residential inventory and from loss of water and power. Figure 3 compares the HAZUS displaced household estimates with ABAG estimates (Perkins et al., 1999) of the number of uninhabitable housing units (corrected for vacant units) projected for these same scenarios for the nine-county area under ABAG jurisdiction (our ten-county study area less Santa Cruz county). The impact of the exclusion of Santa Cruz County in the HAZUS estimates of displaced households in Figure 3 is minimal. Only the San Andreas and San Gregorio scenarios produce displaced households in Santa Cruz counties; the estimates for Santa Cruz county range from about 200 for the San Gregorio-North event to about 1,800 displaced households for the **M**7.9 San Andreas scenario.

As Figure 3 demonstrates, the two approaches yield dramatically different results. ABAG projects more than 150,000 uninhabitable housing units for both a repeat of 1906 and for a full rupture of the Hayward fault. The HAZUS estimates of displaced households for those events are about 59,000 and 24,000, respectively, more than a factor of 2.5 to 6 lower than the ABAG estimates. In our HAZUS calibration run using the

Loma Prieta ShakeMap as input, the projected number of displaced households in our ten county study area is 6310, about a factor of 2.5 less than the actual 16,000 uninhabitable units, indicating that HAZUS is likely seriously underestimating this parameter.

The reasons for the discrepancies in the estimates of uninhabitable housing units are related both to the method of calculation and the building inventory utilized. HAZUS calculates loss of habitability directly from damage to the national residential occupancy inventory and from loss of water and power. In contrast, ABAG's approach is an empirical one calibrated with data from Loma Prieta and Northridge and is applied to a much more detailed and spatially accurate Bay Area housing inventory. In ABAG's case, the water and power factors do not affect the number of uninhabitable units, but rather the peak shelter population. ABAG uses a measure of ground shaking severity proportional to pseudo-velocity response spectra to generate modified Mercalli intensity maps. It then assigns a percentage of uninhabitable units for each intensity level. Since this approach was calibrated in part with Loma Prieta data, it yields the correct number of uninhabitable units for that event (about 13,000 uninhabitable units in the ABAG nine-county jurisdictional area shown in Figure 4, and 16,000 total for our ten-county study area). We believe the ABAG numbers are more realistic because of extensive testing of their model on past Bay Area earthquakes, including 1906 and the 1984 **M**6.2 Morgan Hill.

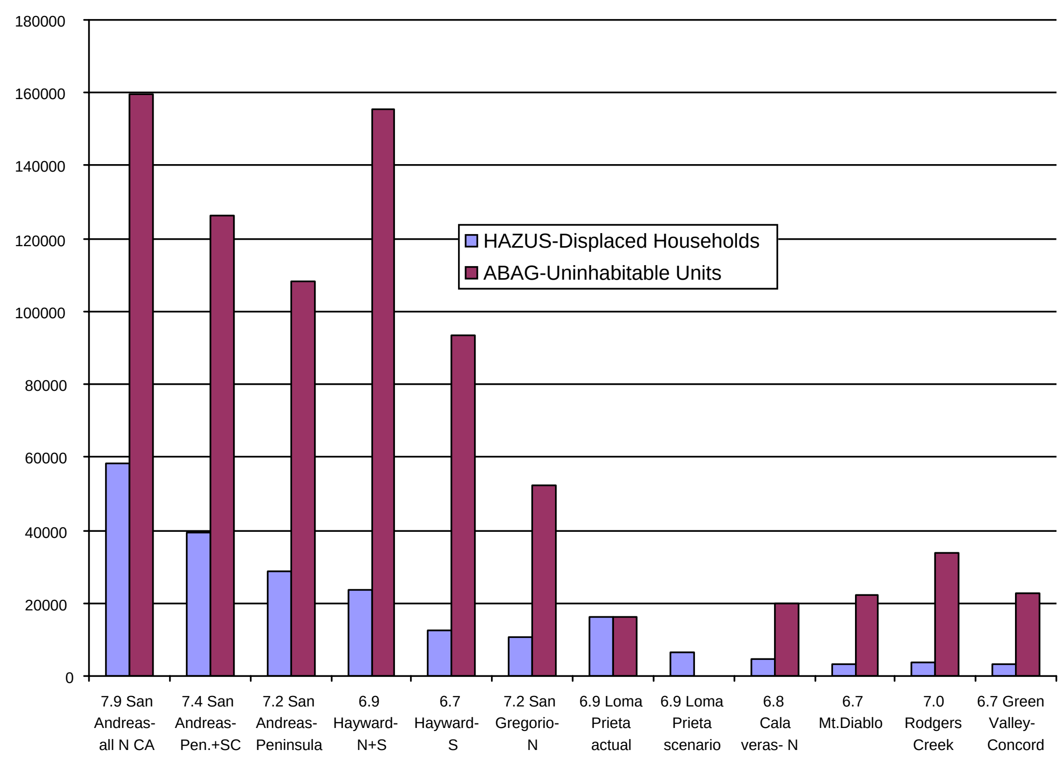


Figure 3. Comparison of HAZUS estimates of displaced households with ABAG estimates of uninhabitable units from ABAG for the nine-county Bay region under ABAG jurisdiction (our ten-county study region less Santa Cruz county).

The ABAG estimates of uninhabitable units suggest all scenario events will have a larger impact on housing than the Loma Prieta earthquake. In fact, six of the ten scenarios will probably result in a greater impact than the 1994 **M**6.7 Northridge earthquake in Los Angeles where over 46,000 housing units were made uninhabitable.

### Fatalities

Another significant measure of the impact of the scenario events is the projected number of fatalities. In HAZUS the fatalities are computed for three different times of day: 2:00AM (residential occupancy), 2:00 PM (split between residential and commercial occupancy) and 5:00 PM (residential and commercial occupancy together with potential "commute" fatalities). In Figure 4 we show predicted fatalities for all three times of day to provide a sense of the range of these values. These results demonstrate the overall success of stringent building codes and enforcement in California. For example, the **M**7.4 San Andreas Peninsula + Santa Cruz Mountains scenario event is forecast to cause slightly more than 200 casualties at 2:00 AM, a number significantly lower than the official estimate of 17,000 dead in the comparable size, **M**7.4 1999 Izmit, Turkey earthquake which also struck in the early morning hours. All Bay Area scenarios predict far fewer fatalities than the approximately 6,000 deaths caused by the 1995 Kobe, Japan **M**6.9 earthquake that occurred in the afternoon directly beneath an urban area with a population of more than 1.52 million people.

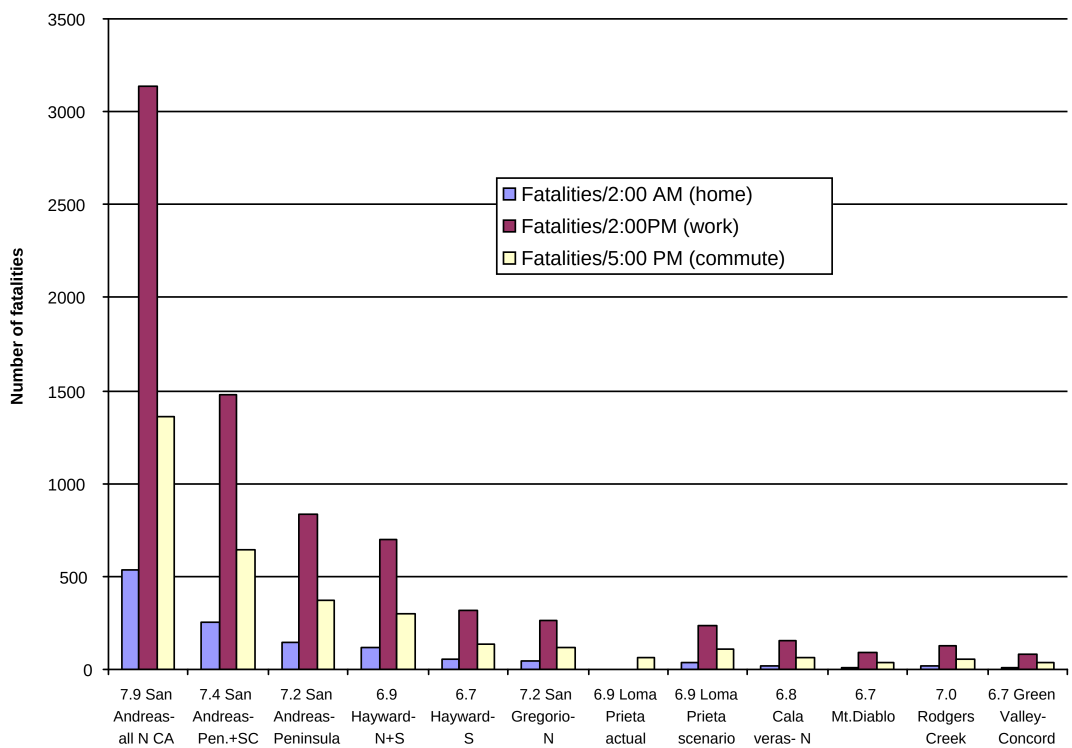


Figure 4. Estimates of fatalities for the ten scenarios for different times of day.

In all cases the predicted number of fatalities are highest for the 2:00 PM scenarios, reflecting the high density of exposed individuals in commercial building of varying seismic vulnerability. These predicted mid-afternoon fatalities are generally about 5 times higher than values predicted at 2:00 AM when all population is assumed to be in residential units.

## Bay Area Annualized Loss Estimates

In contrast to the deterministic scenario loss estimates, which are more local, and relatively short-term, annualized loss estimations are based on very long-term probabilistic seismic hazard potential on a more regional scale. Therefore, the results of annualized loss estimations are best applied to longer-term policy development, mitigation planning and prioritizing, adoption and enforcement of seismic codes, and establishment of guidelines and regulations for earthquake insurance.

Table 2 – Estimated annualized direct economic losses to buildings for the ten-county San Francisco Bay Area study region

| County | 1990 Population | Building Replacement Value (M$) | Annualized Loss (k$) | Per-Capita Loss ($) | Loss Ratio (%) |
|---|---|---|---|---|---|
| Alameda | 1,279,182 | 75,109 | 198,328 | 155 | 0.264 |
| Contra Costa | 803,732 | 43,080 | 81,017 | 101 | 0.188 |
| Marin | 230,096 | 14,490 | 24,705 | 107 | 0.170 |
| Napa | 110,765 | 6,782 | 8,991 | 81 | 0.133 |
| San Francisco | 723,959 | 58,663 | 141,068 | 195 | 0.24 |
| San Mateo | 649,623 | 36,322 | 77,846 | 120 | 0.214 |
| Santa Clara | 1,497,577 | 80,450 | 146,215 | 98 | 0.182 |
| Santa Cruz | 229,734 | 12,518 | 16,754 | 73 | 0.134 |
| Solano | 340,421 | 16,415 | 21,458 | 63 | 0.131 |
| Sonoma | 388,222 | 22,350 | 37,513 | 97 | 0.168 |
| **Total / Average** | **6,253,311** | **366,179** | **753,895** | **121** | **0.206** |

We calculated earthquake losses for the Bay Area using the overall long-term probabilistic seismic shaking hazard. Table 2 presents the summary of the results. This evaluation considers the expected frequency of earthquake occurrence along each fault, estimated from the historical and geologic earthquake activity. Geologists and seismologists at the California Geological Survey (CGS) and the U.S. Geological Survey have worked in collaboration with other geologists and seismologists familiar with California's seismic hazards to include all known seismic sources in and near California. The estimates of ground motion that can be anticipated from these earthquakes incorporate the variability of shaking from different earthquake sources. This analysis, developed jointly by the CGS and the USGS (Petersen et al., 1996), has been recently updated (Frankel et al., 2002). The annualized building damage resulting from the integrated effects of ground shaking emanating from all potential earthquakes is estimated using HAZUS, with the same building inventory that we have used for the scenario calculations.

As Table 2 indicates, our preliminary estimate for the expected direct economic annualized losses to buildings for the ten-county San Francisco Bay Area is $ 754 million. It corresponds to an average annual per-capita loss of $121 and an average annual loss ratio of roughly 0.2%. Counties most affected are Alameda, Santa Clara, and San Francisco, with San Francisco having the largest per-capita annual loss, and Alameda the largest annual loss ratio in the ten-county Bay Area.

## Limitations and Losses and Damage Not Included

We believe that the economic impact of these scenario or similar earthquakes when they actually occur will be far greater than the losses estimated here for a variety of reasons. In our implementation of HAZUS, several factors directly contribute to low estimated losses. We report only losses resulting from shaking damage. Losses related to damage due to liquefaction and earthquake-triggered landsliding were not computed, because we did not supply the required ground failure inputs. Liquefaction and ground failure accounted for more than $10 billion dollars of losses in the M6.9 Kobe Japan earthquake in areas of soil conditions very similar to those in the north Bay region (T.Holzer, U. S. Geological Survey, 2003, personal communication). Another factor minimizes our estimates of losses is unrealistically low costs for repair and replacement of structural and non-structural damage for the Bay Area. These costs are probably significantly underestimated in HAZUS given the phenomenal increase in real-estate value throughout the Bay Area over the past decade (153% increase in median home costs between 1989 and 2000, see http://www.dqnews.com/AA2000BAY02.shtm).

However, the primary reason we believe our loss estimates to be low is the use of the national building and lifeline inventory contained within HAZUS. Our analysis is based on population and a building inventory derived from the 1990 census data (the default in HAZUS99 service release 2). Present Bay Area population is about 7.05 million, more than a 13% increase over the 1990 census value. The past decade or so has seen significant construction throughout the Bay Area. The impact of the lack of a detailed inventory is probably best demonstrated by the factor of 2.5 to 6 between the HAZUS estimates of displaced households and the more detailed ABAG estimates of uninhabitable housing units, discussed in the previous section. Furthermore, HAZUS99 does not include appropriate vulnerability/fragility curves for some key building types in the Bay Area, such as low-rise units with street level garages or open commercial space, so called "soft stories". In fact, a single engineering building type is used in HAZUS to analyze potential damage to all wood-frame construction under 5000 square feet, the dominant form of residential construction in the Bay Area.

Our loss estimates also do not include damage to critical facilities, transportation, and utility lifelines. Although HAZUS has the capability to determine damage to such structures, the default inventory and our implementation (which did not include ground failure input) was not sufficient to adequately cover these systems. Inventories of these facilities for the Bay Area within HAZUS99 were found to be incomplete, and the vulnerabilities of many of these structures were not specified. As a result, damage to key systems and facilities such as drinking water systems (including the Hetch-Hetchy aqueduct), Bay Area ports, and light rail systems were not calculated.

The potential direct and indirect losses due to such infrastructure system failures may be enormous and have significant ripple effects throughout the Bay Area and California economy. For example, the Bay Area Economic Forum (2002) has estimated at least \$28.7 billion in economic losses to the region from interruption of the Hetch Hetchy water supply system by a repeat of the magnitude 7.9 1906 earthquake on the San Andreas fault. Similarly, they estimate \$17.2 billion for disruption caused by a full rupture of the Hayward Fault. These estimates include commercial, industrial, and residential welfare losses of \$18.0 billion and \$11.4 billion for two events respectively, as well as incremental losses of \$10.7 billion and \$5.8 billion respectively due to damage from lack of adequate water supply to suppress post-quake fires. In addition to the quantifiable near-term damage, the report concluded the Bay Area economy would suffer irreversible long-term damage due to the failure of many businesses to reopen because of losses incurred during a disruption, the permanent relocation of other businesses outside the region due to water security concerns, and the reluctance of new businesses to locate here for similar reasons.

## Conclusions

We have computed estimated economic losses, fatalities, and housing impacts for the ten most likely damaging earthquakes forecast to strike the San Francisco Bay Area as determined by the USGS-led Working Group on California Earthquake Probabilities. We have also estimated the average, long-term annualized potential direct economic losses to buildings, using the newly-released USGS-CGS probabilistic ground motion maps.

Because the ten most likely future earthquakes in the Bay area occur on faults throughout the region, the impact and potential losses reported here reveal significant risk for the entire ten-county region, a result corroborated by the annualized loss results. We find that seven of the ten forecasted earthquakes would cause building-related economic losses at least equivalent to the 1989 **M**6.9 Loma Prieta earthquake. The projected number of uninhabitable housing units for all ten scenarios will probably exceed the 16,000 units for Loma Prieta. More than 150,000 uninhabitable housing units are projected for a **M**7.9 repeat of the 1906 earthquake or a **M**6.9 rupture of both the northern and southern segments of the Hayward faults. Estimated numbers of fatalities vary depending on the time of day; a maximum number of slightly more than 3,000 deaths are projected for a repeat of the 1906 earthquake during work hours. Most scenarios have maximum projected fatalities on the order of several hundred. These numbers are significantly lower than the 6,000 deaths caused by the 1995 **M**6.9 Kobe, Japan earthquake and reflect the lower population density, different building types, and the overall success of stringent building codes and enforcement in California.

We found, not surprisingly that the level of exposure adjacent to the faults can be as a significant factor as earthquake magnitude in determining losses and impact. The high level of exposure directly along and adjacent to the Hayward faults results in values of uninhabitable housing units and building-related economic losses greater than that projected for several larger earthquakes.

For the annualized loss case, the rough estimate is that the earthquake-induced ground motion, on average is costing every resident of the ten-county San Francisco Bay Area $120 each year. This per-capita loss, which is the direct building economic damage only, is close to $200 for San Francisco residents. The annualized loss estimates further indicate that, on average, the long-term earthquake ground motion hazards translate into a reduction of building inventory values of 0.2% each year.

Our loss values undoubtedly underestimate the economic impact of the scenario earthquakes. The HAZUS99 service release 2 we used in our analysis relies on population and building inventory based on the 1990 census. Present Bay Area population is about 7.05 million, more than a 13% increase over the 1990 census value, and there has been substantial construction throughout the Bay area during the 1990's. An ABAG analysis of post-earthquake housing needs using a refined Bay Area residential inventory suggests HAZUS estimates of displaced households are a factor of 2.5 to 6 too low, implying that HAZUS, in general, may be underestimating structural damage. Furthermore, our results do not include losses due to damage to critical facilities, transportation and utility system lifelines. Although HAZUS has the capability to determine damage to such structures, inventories of these facilities for the Bay Area in HAZUS were found to be quite incomplete, and the vulnerabilities of some of some structures were not specified. As a result, damage to key systems and facilities such as drinking water systems, Bay Area ports, and light rail systems were not calculated. HAZUS also does not calculate the significant ripple effects of damage to lifelines on the economy of the Bay Area and of California. Nevertheless, these estimates of casualties and damage to structures, combined with the probabilities of these events, provide residents and decision makers in the San Francisco Bay Area with vital information to assess their exposure and prepare for and mitigate against similar, or larger future damaging earthquakes.

## References

Bay Area Economic Forum, 2002. Hetch Hetchy water and the Bay Area economy, report issued October, 2002, 60 p., on line at: http://www.bayeconfor.org/pdf/hetchhetchyfinal2.pdf

Davis, J. F., Bennett, J. H., Borchardt, G. A., Kahle, J. E., Rice, S. J., and Silva, M. A. 1982, Earthquake planning scenario for a magnitude 8.3 earthquake on the San Andreas Fault in the San Francisco Bay area: California Geological Survey, Spec. Publ. 61, 160 p.

FEMA, 1992, NEHRP handbook for the seismic evaluation of existing buildings: Federal Emergency Management 178, Washington, D. C.

Frankel, A.D., Petersen, M. D., Mueller, C. S., Haller, K. M., Wheeler, R. L, Leyendecker, E. V., Wesson, R. L., Harmsen, S. C., Cramer, C. H., Perkins, D. M., and Rukstales, K. S., 2002, Documentation for the 2002 update of the National Seismic Hazard Maps: U. S. Geological Survey Open-File Report 02-420, 33 p., online at: http://pubs.usgs.gov/of/2002/ofr-02-420.

Perkins, J. B., 1999, On Shaky Ground - Bay Area Shaking Hazard Maps (Update reflecting October 1999 USGS earthquake probability estimates), Association of Bay Area Governments, online only at: http://quake.abag.ca.gov/mapsba.html.

Perkins, J. B., 1998, On Shaky Ground - Supplement - A Guide to Assessing Impacts of Future Earthquakes Using Ground Shaking Hazard Maps for the San Francisco Bay Area*:* Association of Bay Area Governments, Oakland, CA, 28 pages.

Perkins, J. B., and Boatwright, J., 1995, The San Francisco Bay Area -- On Shaky Ground: Association of Bay Area Governments, Oakland, CA, 56 pages. [Companion multimedia CD-ROM in 1996.]

Perkins, J.B., Mikulis, K., and Kirking, B., 1999, Preventing the Nightmare - Designing a Model Program to Encourage Owners of Homes and Apartments to Do Earthquake Retrofits: Association of Bay Area Governments: Oakland, 25 pp.

Petersen, M. D., A. D. Frankel, J. J. Lienkaemper, et al., 1996, Probabilistic Seismic Hazard Assessment for the State of California*:* California Dept. of Conservation Open-File Report 96-08, U. S. Geological Survey Open-File Report 96-706.

Steinbrugge, K.V., Bennett, J.H, Lagorio, H.J., Davis, J.F., Borchardt, Glenn, and Toppozada, T.R, 1987, Earthquake planning scenario for a magnitude 7.5 earthquake on the Hayward fault in the San Francisco Bay area: California Geological Survey, Spec. Publ. 78, 245 p.

Toppozada, T.R, Borchardt, Glenn, Hallstrom, C.L., and Youngs, L.G 1994, Planning scenario for a major earthquake on the Rodgers Creek fault in the Northern San Francisco Bay area, California Geological Survey, Spec. Publ. 112, 265 p.

Wald, D. J., V. Quitoriano, T. H. Heaton, and H. Kanamori, 1999a, Relationships between peak ground acceleration, peak ground velocity and modified mercalli intensity in California: Earthquake Spectra, Vol. 15, No. 3, 557-564.

Wald, D. J., V. Quitoriano, T. H. Heaton, H. Kanamori, C. W. Scrivner, and C. B. Worden, 1999b, TriNet "ShakeMaps": Rapid generation of instrumental ground motion and intensity maps for earthquakes in southern California: Earthquake Spectra , 15 , 537-556

Wills, C.J., M. Petersen, W.A. Bryant, M. Reichle, G.J. Saucedo, S. Tan, G. Taylor, and J. Treiman, 2000, A site-conditions map for California based on geology and shear-wave velocity: Bull. Seism. Soc. Am., V. 90, No. 6, pp. 187-208.

Working Group on California Earthquake Probabilities, 2003, Earthquake probabilities in the San Francisco Bay Region: 2002– 2031: U. S. Geological Survey Professional Paper, in press.

U. S. Census Bureau, 2000, Factfinder for the nation, U. S. Census Bureau fact sheet CFF-4, online at: http://census.gov/prod/2000pubs/cff-4.pdf.